APSS Apollo Application Note on

Micro Ring Resonator

Computer-Aided Design and Simulation

APN-APSS-RingResonator

Apollo Inc.
1057 Main Street West
Hamilton, Ontario L8S 1B7
Canada
Tel: (905)-524-3030
Fax: (905)-524-3050

www.apollophotonics.com

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Abstract

This application note describes how to design, simulate, and layout a double-ring resonator using the Apollo Photonics Solution Suite (APSS).

This application note:

- describes the operation principle
- discusses key issues affecting double-ring resonator design, such as free spectral range, finesse, insertion loss, and polarization dependence
- describes how the APSS Circuit Module (CM) can be used to break a complicated component into its logical sub-components, which can then be more efficiently analyzed, and result in more accurate simulations
- describes the procedures for mask layout and exporting

Keywords

APSS, finite-difference time-domain (FDTD), circuit module, ring resonator, free spectral range (FSR), finesse, perfectly-matched layer (PML), polarization dependent loss (PDL)

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1 Introduction

Micro-ring resonators are versatile wavelength-selective elements that can be used to synthesize a wide class of filter functions [1] and [2]. Many theoretical designs have been proposed to optimize the filter response and other properties using various coupled-resonator arrays [3] and [4], while compact resonators have been demonstrated in a number of semiconductor materials [5] through [7] and glass waveguides [8]. The experimental performance, however, has been far from ideal for single micro-resonators and arrays – leaving a wide gap between theory and practice. This gap is partly due to fabrication-related issues associated with the small size of the resonators, and partly due to fundamental issues associated with the highly confined waveguides that constitute these devices. One of the critical issues of the ring-resonators is polarization sensitivity, which limits their applications in fiber-optic communication systems in which the polarization states of optical signals may change randomly over time.

The most common method to simulate the ring resonator is the finite-difference time-domain (FDTD) method. FDTD is a useful method, but requires a large amount of memory and long computation time. Using FDTD, it becomes very inefficient and even impossible to simulate 3-D models on most PCs available today.

The APSS Circuit Module (APSS-CM), however, allows the optical designer to divide a complex structure, such as a double-ring resonator, into a number of logical sub-components. Each of these components can then be simulated individually by suitable methods in the Device Module (APSS-DM), and finally reassembled using the APSS-CM. Another advantage of using the APSS-CM is that simulation of identical devices does not have to be repeated, no matter how many they are used in the circuit.

The resonator device used as an example in this document is made up of two identical couplers, two half-circle connectors, and four terminals.

2 Theory

2.1 Operation principle

As shown in Figure 1, multiple wavelengths input into Terminal 1 will be partially coupled into the ring through Coupler 1. The optical wave in the ring will be partially coupled into the straight waveguide through Coupler 2 and outputs from Terminal 2.

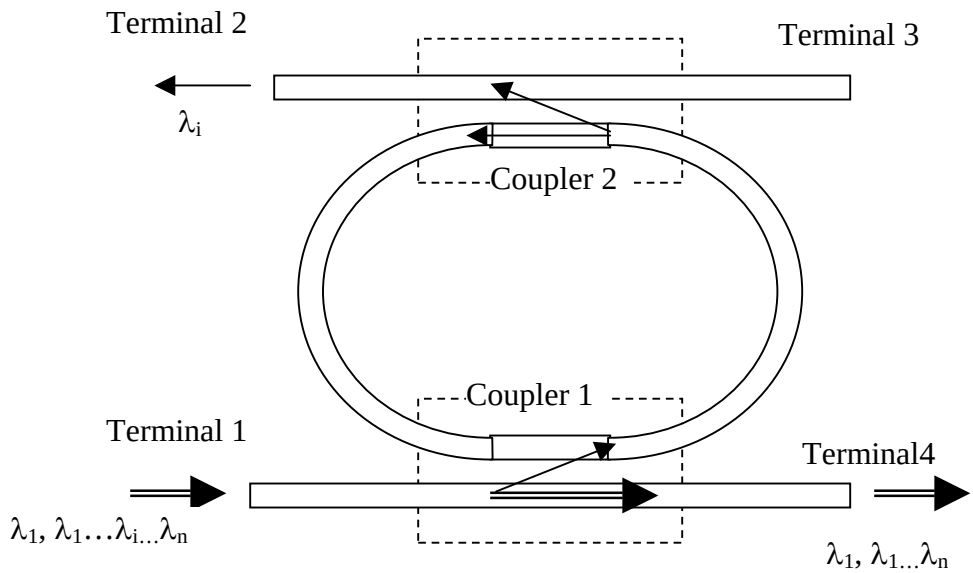


Figure 1 Schematic diagram of a ring resonator

If the wavelength, for example, λ_i satisfies the resonant condition, that is,

$$n_{eff} L = m\lambda_i$$

the coupling of the wave with wavelength λ_i will be enhanced and all others will be suppressed. As a result, only λ_i will be dropped from Terminal 2, while the rest of the wavelengths will pass through and output from Terminal 4. Here n_{eff} is the effective index of the bending waveguide, L is length of the ring, and m is an integer.

2.2 Free spectral range

Free spectral range (FSR) is one of the key specifications of the ring resonator. It is defined as:

$$FSR = \frac{\lambda_i^2}{n_{eff} L} \approx \frac{\lambda_i^2}{n_{eff}\left(2\pi R + 2L_c\right)}$$

where R is the ring radius and L_c is the coupler length.

Because FSR is inversely proportional to the size of the ring resonator, the ring must be small in order to achieve a high FSR. For instance, the ring radius should only be approximately 8μm if it is built on InGaAsP/InP (n_{eff} ~3.3) with FSR=10nm and λ_i=1550nm, assuming the coupler length is about 10μm each. However, the ring radius could be adjusted to 20μm for FSR=5nm.

2.3 Finesse

The finesse is another key specification of the ring resonator and it is defined as [8]:

$$F = \frac{FSR}{\Delta\lambda_{FWHM}} = \frac{\pi}{2\sin^{-1}\left(\frac{1-R}{2\sqrt{R}}\right)}$$

where:

$$R = e^{-\alpha}\left(1-\kappa\right)$$

Here α is the total amplitude attenuation coefficient for each round trip, and κ is the normalized coupling coefficient of the coupler.

It is obvious from the formula that F is dependent on both the internal loss and the coupling (that is, the external loss) of the resonator. The higher the total losses are, the lower the finesse of the resonator.

It is almost always advantageous to reduce both the internal and external losses in order to obtain higher finesse. However, the external loss due to coupling is necessary and cannot be too small for the resonator to operate as an optical filter. If the external loss is smaller than the internal loss, all the coupled power will be lost inside the cavity and no power will be coupled out. Because of these constraints, the ring resonator must use a

strongly guided waveguide to minimize the bending loss for a curved waveguide with a very small radius.

2.4 Multiple ring resonator

To increase the finesse, two or more rings could be used as shown in Figure 2. In this case, the combined finesse becomes:

$$F_t = \frac{FSR_t}{\Delta\lambda_t}$$

which is increased since the combined FSR:

$$FSR_t = N \cdot FSR_1 = M \cdot FSR_2$$

is enlarged and the combined FWHM bandwidth:

$$\Delta\lambda_t = \frac{\Delta\lambda_1 \Delta\lambda_2}{\Delta\lambda_1 + \Delta\lambda_2}$$

is reduced accordingly.

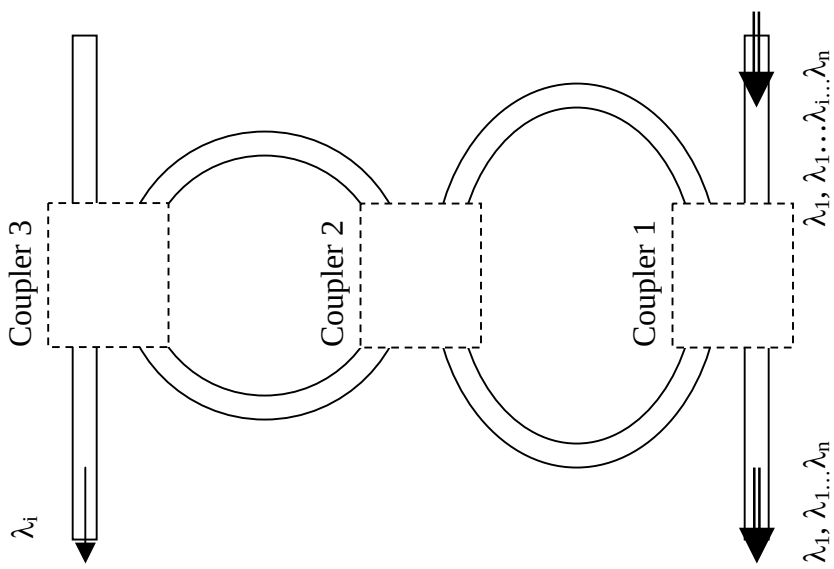
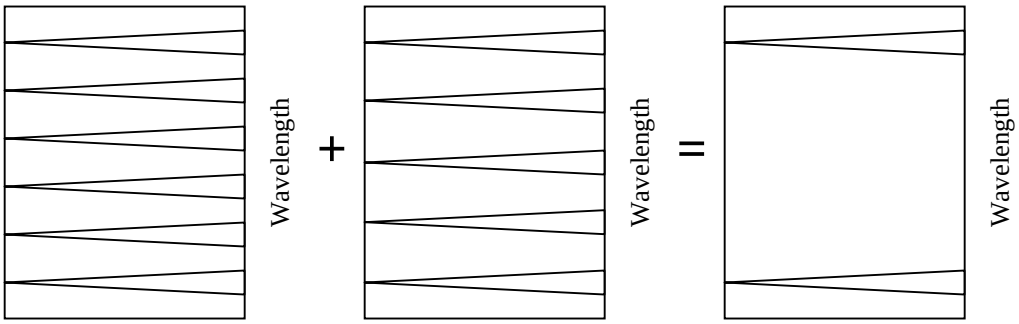


Figure 2 Schematic diagram of a multiple rings resonator

The two resonators have to be carefully designed to make sure that both N and M are integers. This way, the N-th peak of the resonator 1 located at the same wavelength as the

M-th peak of the resonator 2 results in a sharper peak (high finesse). All the others peaks are blocked by each other as illustrated in Figure 3.



(a) Resonator 1 (b) Resonator 2 (c) Combination

Figure 3 Enhancement and cancellation of a two rings resonator

3 Design and Simulation

3.1 Overall design

The design goal is to design a low insertion-loss and polarization independent resonator with 100 GHz (~0.8nm) FSR similar to that reported in [7]. The overall size is about 15 X 50 mm^2. It is impossible perform an FDTD simulation for such a large structure using readily available computation resources. Even a 2-D version of this structure is too much for the FDTD method, while a 3-D simulation is completely impossible given computational constraints.

However, using the APSS-CM, the double-rings resonator can be disassembled into three couplers, four half-circle connectors, and four terminals, as shown in Figure 4. None of these sub-components produce any reflection, so FDTD simulation is not necessary, and a beam propagation method (BPM) simulation is sufficient for the analysis. Even a full 3-D simulation is possible.

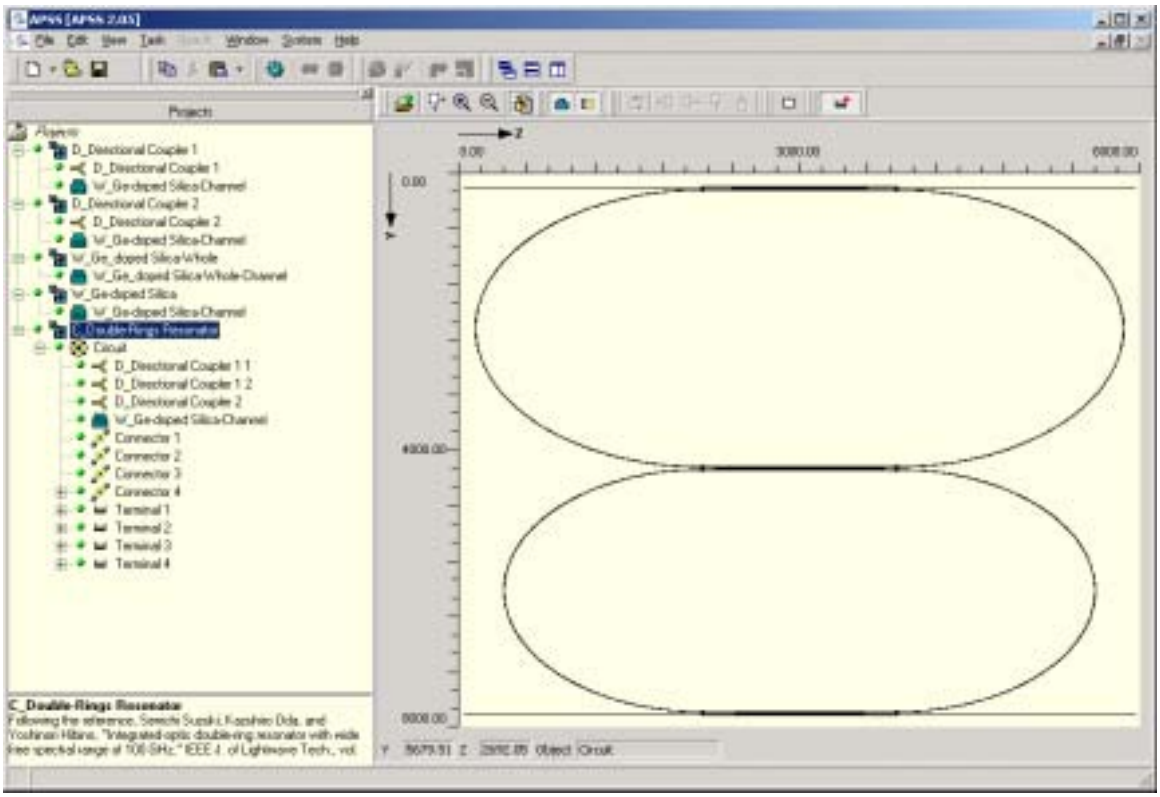


Figure 4 Layout of the circuit project for a double-rings resonator.

3.2 Material Design

Following the reference first created a material project, “M_Ge-doped SiO2, dn=1.5%” with two materials only. One is the pure silica and another one is Ge-doped with 1.5% index difference as shown in Figure 5.

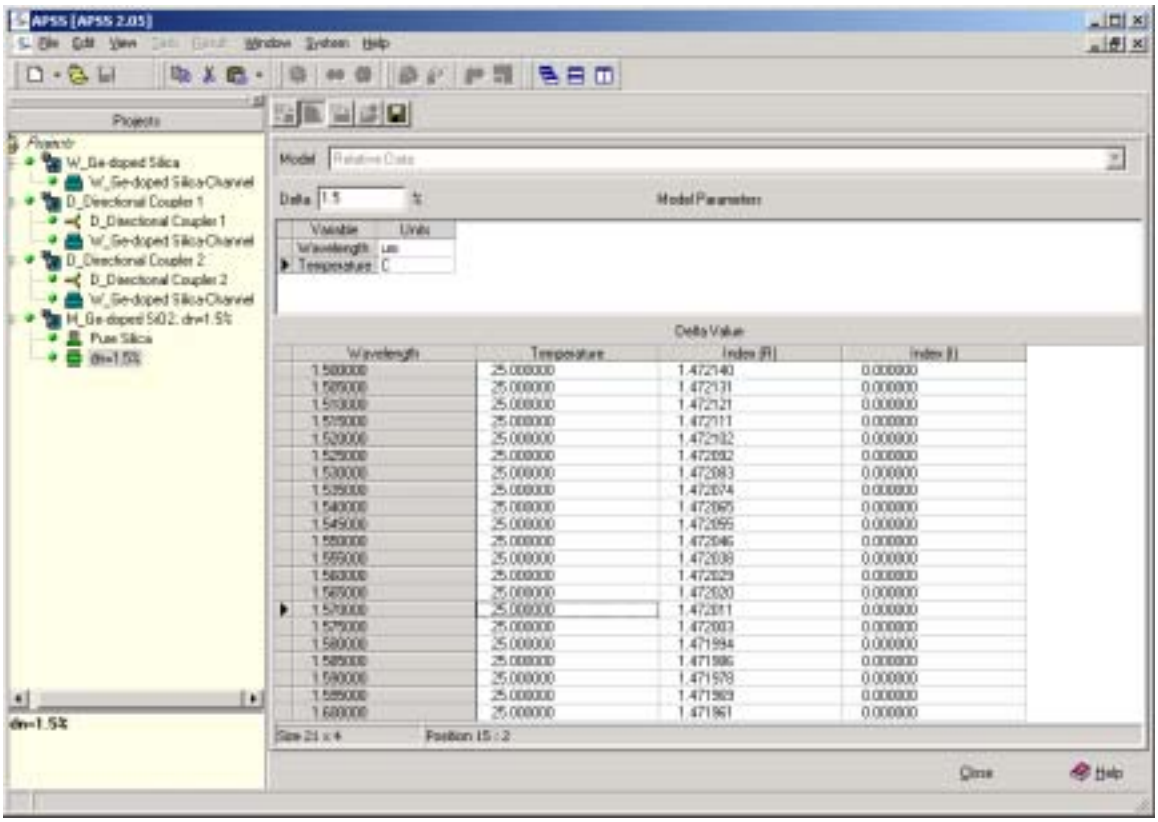


Figure 5 Material project for the double-rings resonator.

3.3 Waveguide Design

Figure 6 shows a square channel waveguide project built on the two materials that were defined in the material project. By taking advantage of the geometric symmetry of the structure, only one half of the structure needs to be designed. The geometric parameters are shown under the structure in Figure 6.

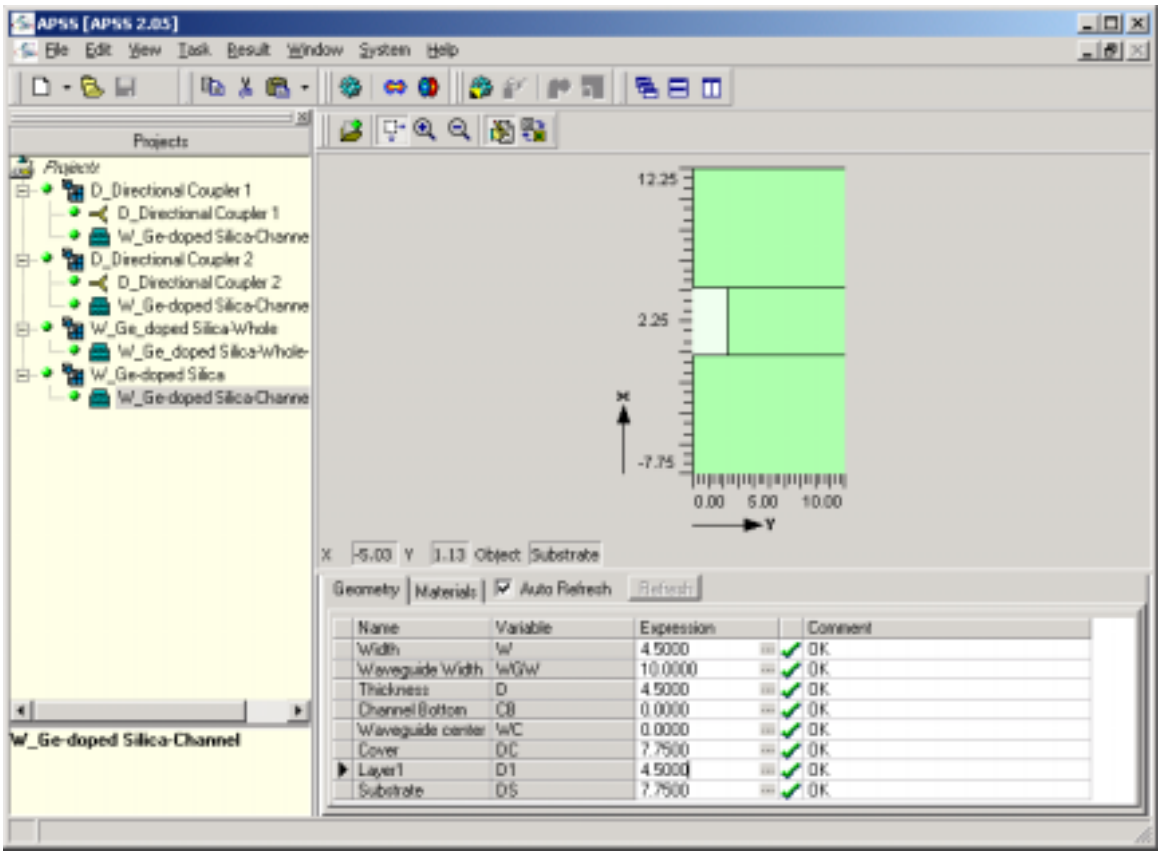


Figure 6 Waveguide project for the double-ring resonator

Shown in Figure 7 are the calculated dispersion curves for both X- and Y-polarizations. They are exactly the same and polarization independence is preserved.

The mesh setting must be used correctly to achieve accurate results. For this case, 80 X 40 meshes are used to ensure the mesh boundaries are coincident with the dielectric boundaries, as well as being the same size in both directions.

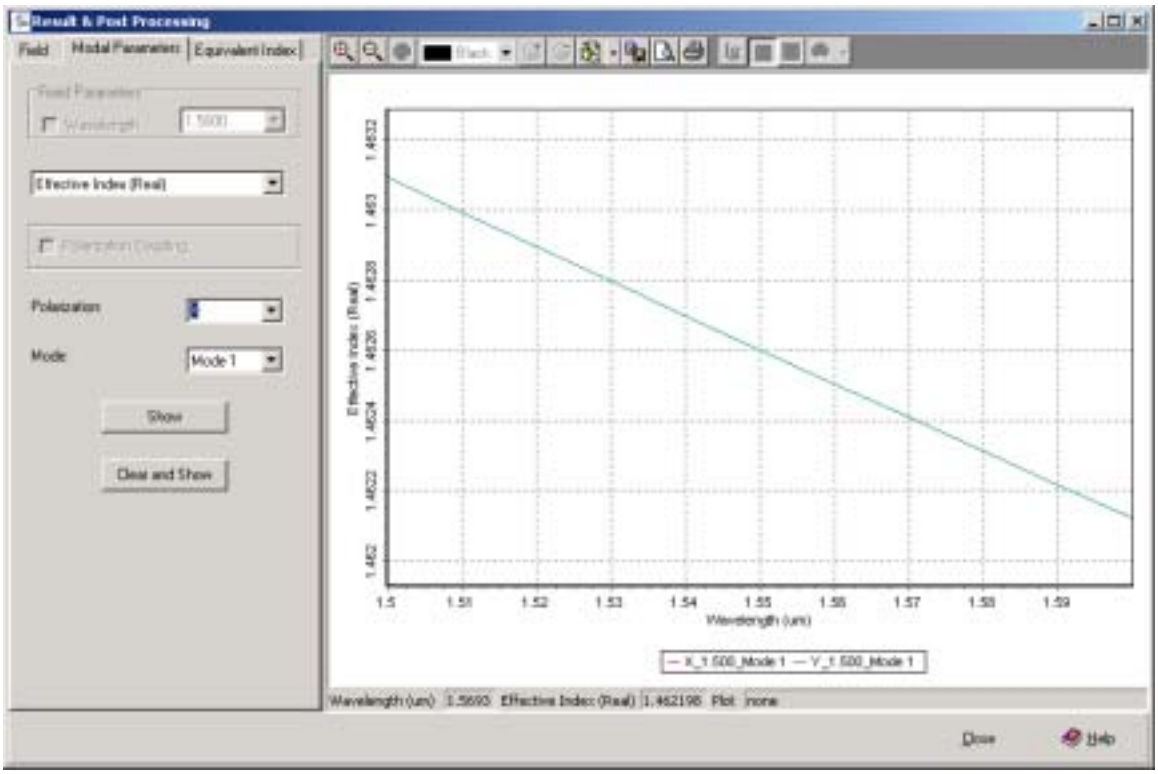


Figure 7 Dispersion curves of the waveguide.

Because the waveguide will be used to build both straight and curved waveguides, bend loss must also be considered. The whole waveguide structure and perfectly-matched layer (PML) boundary condition must be part of the bend loss calculation. Because the leaky wave will mainly travel to the right side, PML can be applied on the right side (Y_{max} side) to save some resources and, most importantly, to avoid spurious modes and non-physical loss/gain that can result from unnecessary use of PML.

For some applications, the waveguide may also leak in other directions, for example, it can leak to the substrate. PML should be applied to any boundary where the wave travels, so that the leakage can be absorbed completely without any reflection.

Figure 8 shows the bending loss for both polarizations. It can be observed that instead of loss, there is a very tiny gain at the bending radius R=1.75mm as used in the reference. This is due to the unnecessary PML boundary condition, because there are no wavelength leaks for this waveguide at such a bent radius.

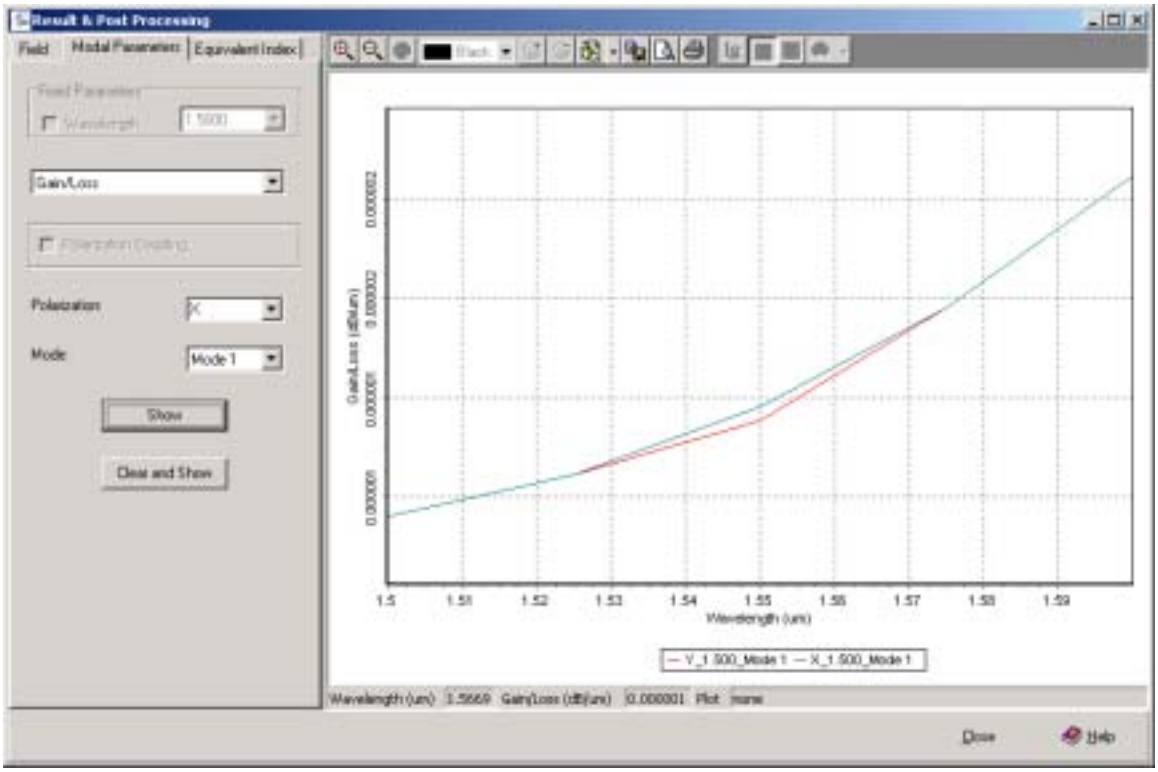


Figure 8 Bending loss of the waveguide.

Because of the bending, the modal profile will shift to one side and the modal symmetry is no longer preserved, as shown in Figure 9. As a result, the waveguide becomes slightly polarization dependent. Therefore, polarization dependence of a bent waveguide is another consideration for phase sensitive devices, and it should always be checked, even if the straight waveguide is polarization independent.

A small difference of 10^{-6} in effective indexes of both polarizations can be found. The length which causes a π phase shift between two polarization is:

$$L = \frac{\lambda}{2\Delta n_{eff}} \approx 775mm$$

Compared with the round trip of the ring, it can be concluded that such a small polarization dependence is not a significant issue.

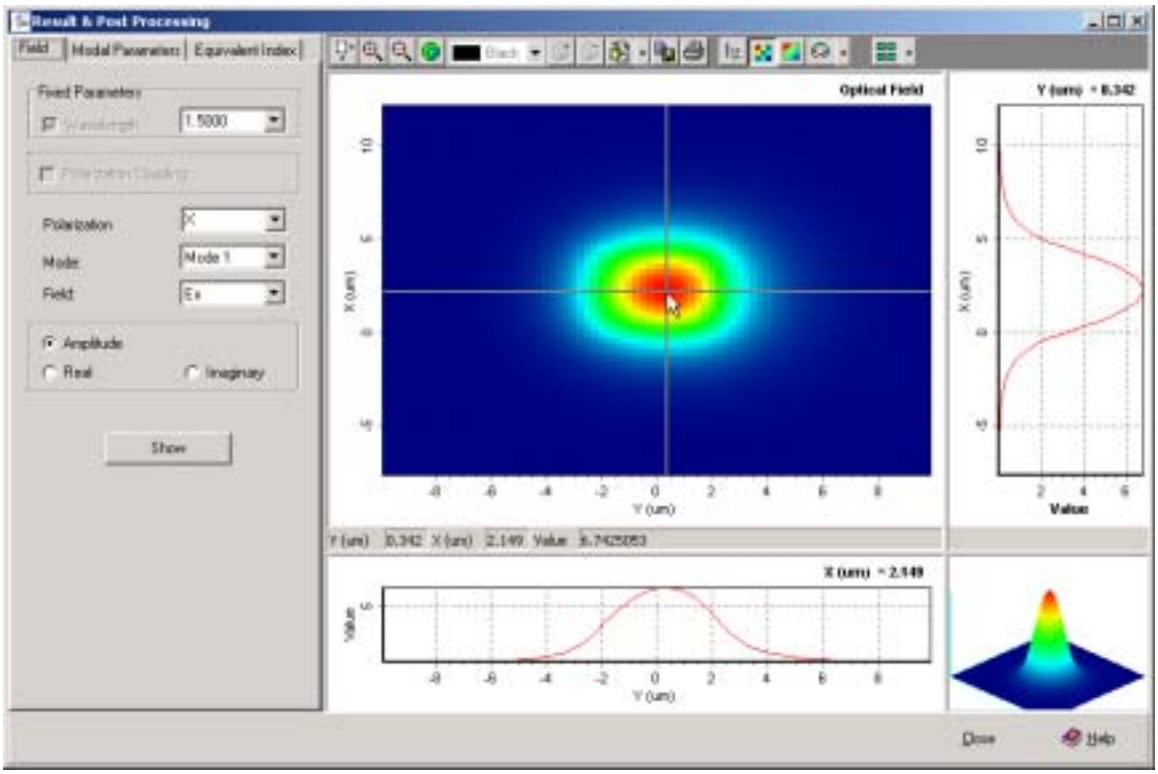


Figure 9 Asymmetric modal profile of a bent waveguide.

3.4 Coupler Design

The coupler used is a directional coupler based on the waveguide designed early, with a fixed coupling ratio. It ensures that only partial power is coupled into the ring from the straight waveguide and that the majority will go through.

Following the reference [7], two directional couplers were designed. One was designed with an approximate 35% coupling coefficient and the other was designed with an approximate 22% coupling coefficient. The one with stronger coupling was used on both sides as Coupler 1 and Coupler 3 (as shown in Figure 2), and the one with weaker coupling was used in the middle as Coupler 2.

Figure 10 shows the layout of a device project for a directional coupler. The shift of the S-bend is estimated at 13μm, based on the 5mm bend radius of the S-bend from the reference.

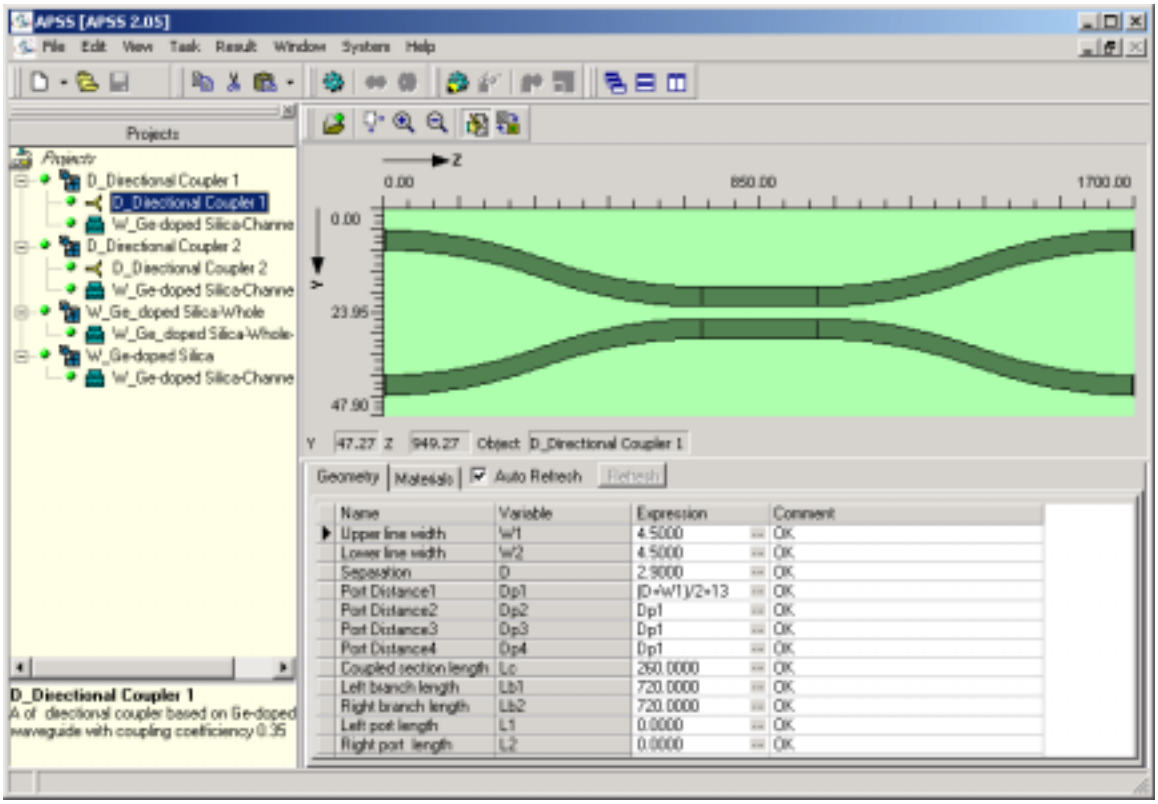


Figure 10 Device project of a directional coupler

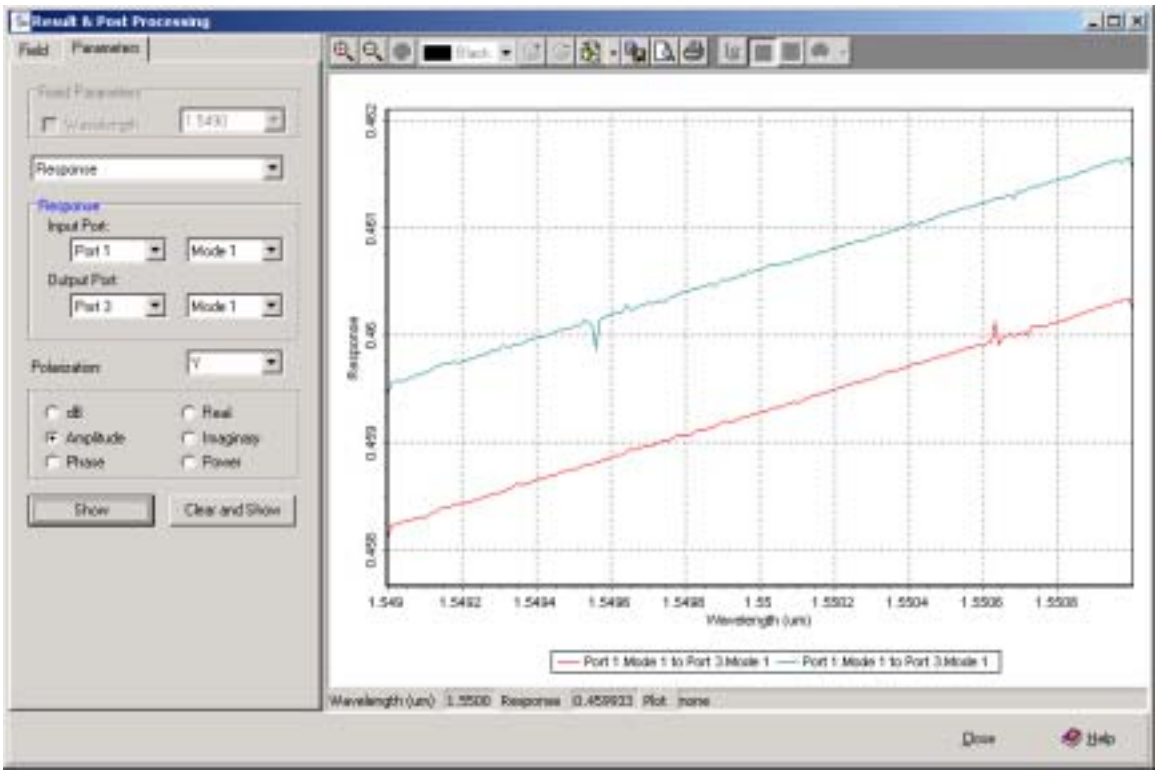


Figure 11 Coupling coefficient of the directional coupler

Figure 11 shows the coupling ratios of the coupler for both polarizations. The ratios are about 0.46, which is higher than they were estimated to be in the reference [7]. A very small polarization dependent loss (PDL), which is about 0.025dB, can be observed as shown in Figure 12, as a result of the bent waveguides.

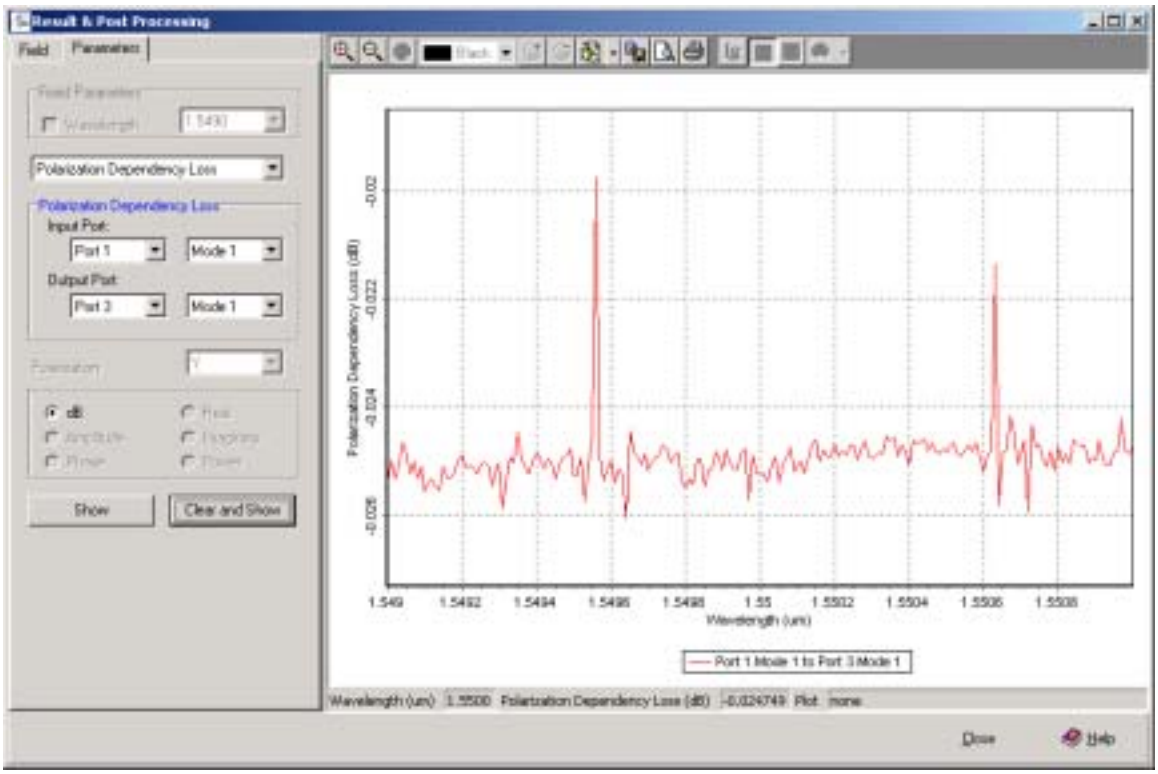


Figure 12 Coupling coefficient of the directional coupler

Similarly, the 2nd directional coupler with 3.4μm gap was simulated. The coupling coefficient was about 0.32 and the PDL was similar at about 0.025dB.

3.5 Circuit design

3.5.1 Layout

Figure 4 shows the layout of the circuit project for the double-ring resonator. It is important to make sure that devices and terminals are in appropriate positions relative to each other. The starting position of each device uses the coordinates of the left-top corner of the rectangular box for each device. To keep the accurate port-to-port relative position, the devices have to be well aligned. For example, in order to make sure the bending radius is 1.75mm, we have to align them at the same place in the Z-direction, and make sure they are separated by $G = g_1 + 2R - g_2 = 3533.9\mu m$ in the Y-direction as shown in Figure 13.

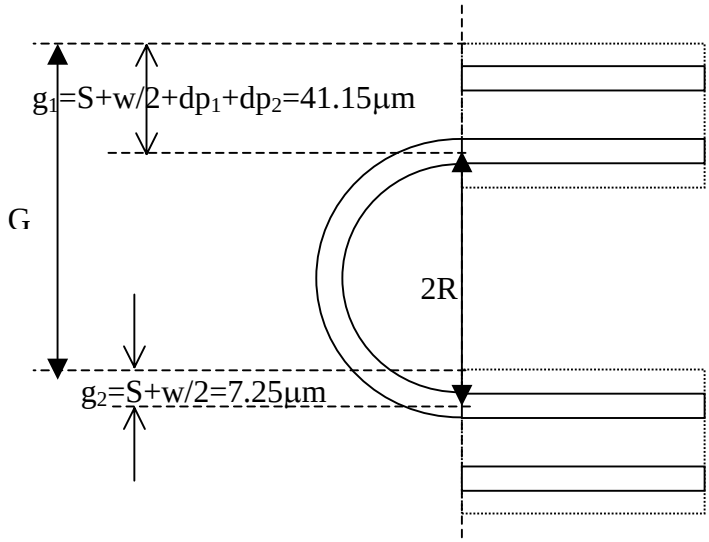


Figure 13 Relative positions among devices

3.5.2 Connectors

Based on the orientation and relative position, the connector type is pre-determined. However, designers are still able to adjust the geometric parameters from the default values. For instance, as shown in Figure 14, the bend radius can be changed to make a half-elliptic shape instead of using the default half circle.

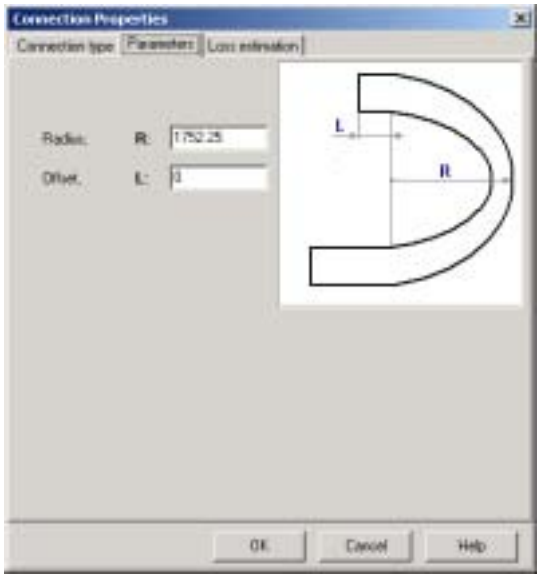


Figure 14 Adjustable connector parameters

Note: "Radius" is defined here as being from the outer boundary of the waveguide, instead of the center. For this reason, the difference of half-width should also be considered in design and calculations.

3.5.3 Solver settings

The choices for circuit solver settings are logically limited because most settings, such as wavelength range, the number of wavelengths, and the available polarizations, are pre-determined by the loaded devices. However, there are many options for the connector solver settings. For example, the default analytical solver, which is fast and less precise when large bend loss is involved, can be switched to a 2-D or 3-D numerical solver, or even to a 3-D full-vector solver.

The default analytical solver is sufficient for most applications when the bend loss is low, because the connector's contribution is only a phase shift. However, a numerical solver or 3-D vector solver is recommended when the bend loss is high.

3.5.4 Simulation results

Figure 15 shows the simulated dropped signals from Terminal 3 of the constructed ring resonator for both X- and Y-polarizations. Enhancement and cancellation of resonance can be clearly observed.

However, the performance is not satisfactory as expected. Because this circuit is very phase sensitive, a fine tuning mechanism is needed to refine the design (for example, the thin film heaters used in the reference could be applied).

Some polarization dependence can also be observed. This can be solved by tuning the phase of the resonators to move the enhanced peaks of both polarizations to the same wavelength.

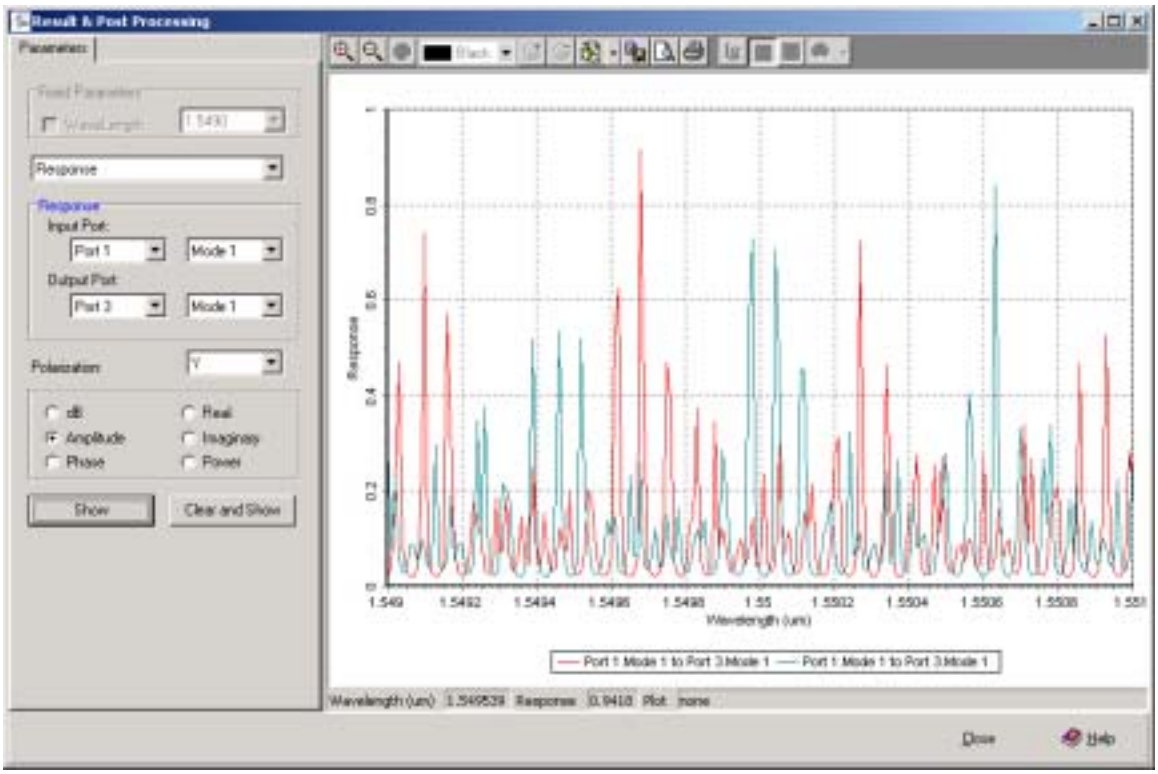


Figure 15 Calculated dropped signal from the Terminal 3 for input from Terminal 1

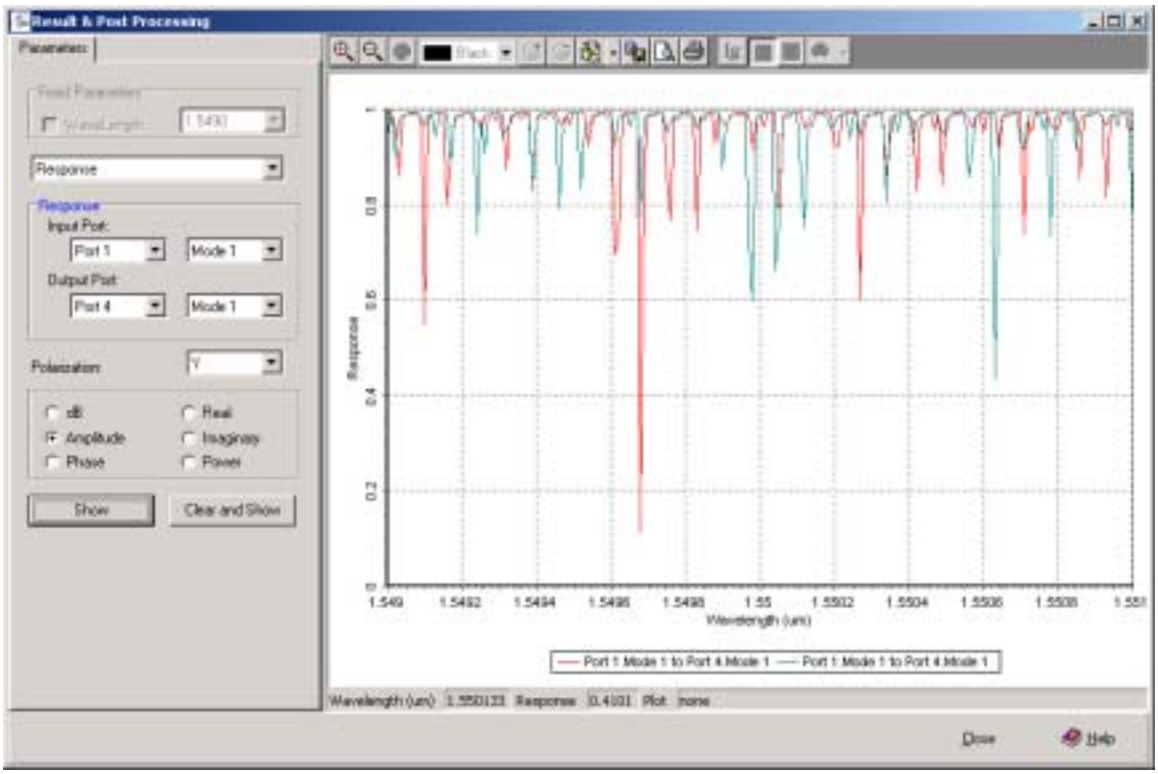


Figure 16 Calculated going-through signal from the Terminal 4 for input from Terminal 1

Figure 16 shows the simulated through signals from the Terminal 4 of the constructed ring resonator for both X- and Y-polarizations.

3.5.5 Exporting projects and files

There are two ways to export: export the project or export the layout mask files.

To export the project, all the project information, including material, waveguide, and devices, can be exported to a APSS file "*.apx", which can be imported by APSS later.

When geometric layout mask files are exported, they are saved to an AutoCAD file "*.dxf", or a GDSII file "*.gds", which can be imported by some mask layout software, as shown in Figure 17.

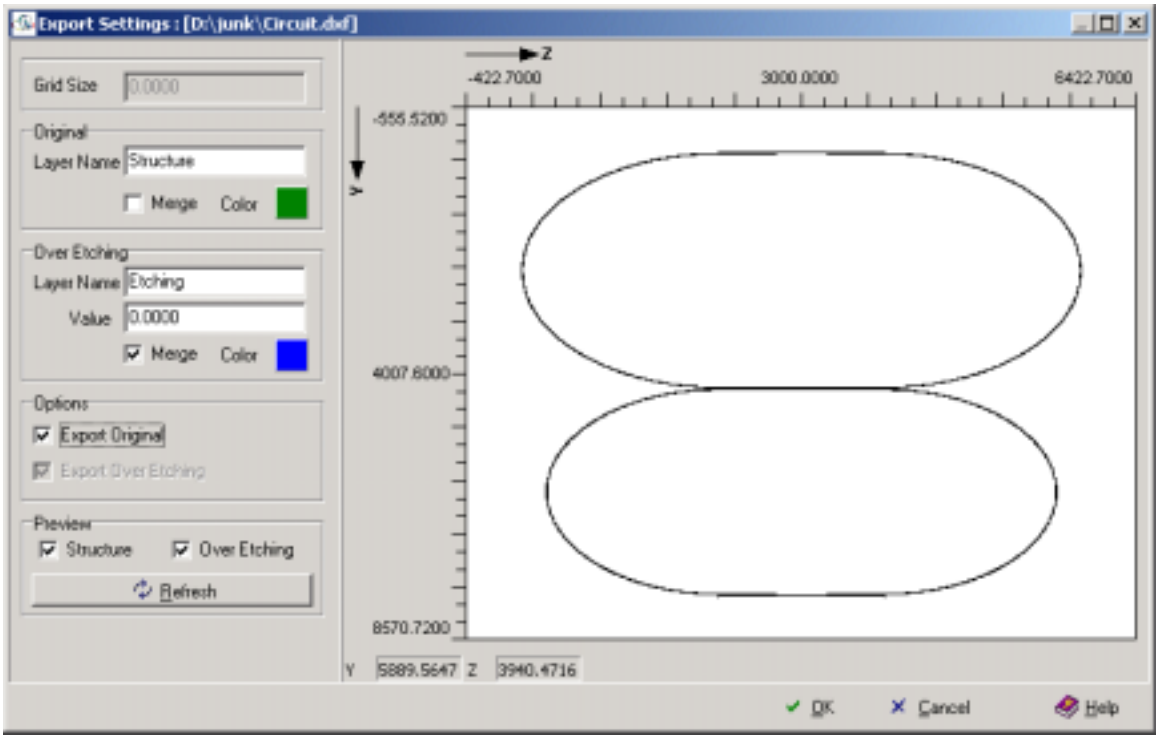


Figure 17 Mask layout file export of the circuit

> ***Note:*** Terminals are not exported to the mask layout file because they are only symbolically represented in the current example. If designers want to include terminals in the layout, straight waveguide devices or straight connectors must be used.

4 Discussion

The APSS-CM provides a convenient platform to disassemble a large and complex structure into smaller pieces. This process greatly facilitates the process of making the required calculations and performing the necessary analysis. How to optimize the design is a separate issue and is beyond the scope of this application note.

To improve the performance of the resonator, a designer could go back to the APSS Devices Module and/or the APSS Waveguide Module to fine-tune the waveguide structure and the coupler. The most critical issues are summarized as follows:

- Polarization independent waveguides must be considered, especially for the curved waveguide at the required bending radius, which directly affects the resonant wavelength. Polarization independence applies to both phase and amplitude, which correspondence to effective index and bending loss of the waveguide.
- Polarization independent couplers with a fixed ratio must be considered. The coupling ratio directly affects the finesse of the ring resonator. On one hand, the ratio cannot be too big in order to achieve high finesse (narrow bandwidth) since the FSR is usually very small. On the other hand, the ratio cannot be too small because the power coupled into the ring has to be enough to compensate for the loss. Otherwise, there will be no sign to drop, and all the power will be lost inside the ring during the oscillation.
- Polarization dependence should be balanced. Since the polarization dependence cannot be completely eliminated in each part, it can be managed in such a way that it effectively cancels itself out. For example, the TE mode can be designed to have a higher coupling ratio in the coupler, but more loss in the curved waveguide.
- Most important, a fine tuning mechanism must usually be introduced because draft designs always have some imperfections that result from uncertainties in the material and fabrication process.

5 Summary and conclusion

As demonstrated with a practical example, APSS offers designers a feasible and efficient way to design and simulate a large, complex, integrated component by disassembling the structure into discreet sub-components for separate analysis.

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